OSP 64387

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	7/17/98	End-of-the-Year 6/1/97 - 5/31/98

4. TITLE AND SUBTITLE
Experiments with Trapped Neutral Atoms

5. FUNDING NUMBERS
N00014-96-1-0485

6. AUTHOR(S)
Prof. Wolfgang Ketterle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
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Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
96PR02383-00

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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17 July 1998

Dr. Peter J. Reynolds, ONR 331
Program Officer
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

In accordance with the terms of the Office of Naval Research Grant No. N00014-96-1-0485, I am sending you the following material:

Type of Material:	End-of-the-Year Report
Title:	Experiments with Trapped Neutral Atoms
Submitted by:	Prof. Wolfgang Ketterle
Period Covered:	June 1, 1997 - May 31, 1998
Number of Copies:	Three plus Form 298
Distribution:	Navy Distribution List (4)

Thank you. Please contact me if you have any questions or comments.

Mary S. Greene
RLE Financial Assistant, Room 36-437

cc: Prof. Ketterle (1)
A.F. Favaloro, E19-750
File (1)

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OFFICE OF NAVAL RESEARCH

END-OF-THE-YEAR REPORT

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/STUDENTS REPORT

for

GRANT or CONTRACT: N00014-96-1-0485

PR Number 96PR02383-00

Title of GRANT or CONTRACT
Experiments with Trapped Neutral Atoms

Name(s) of Principal Investigators
Wolfgang Ketterle

Name of Organization
Massachusetts Institute of Technology

Address of Organization
77 Massachusetts Avenue
Cambridge, MA 02139

Date Submitted
7/4/98

Period covered
6/1/97 - 5/31/98
(1 year)

PART I

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT

PR Number: 96PR02383-00
Contract/Grant Number: N00014-96-1-0485
Contract/Grant Title: Experiments with Trapped Neutral Atoms
Principal Investigator: Wolfgang Ketterle
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a. Number of papers submitted to refereed journals, but not published: 5
b. + Number of papers published in refereed journals (for each, provide a complete citation): 8
c. + Number of books or chapters submitted, but not yet published: 1
d. + Number of books or chapters published (for each, provide a complete citation): none
e. + Number of printed technical reports/non-refereed papers (for each, provide a complete citation): 3
f. Number of patents filed: none
g. Number of patents granted (for each, provide a complete citation): none
h. + Number of invited presentations (for each, provide a complete citation): 12
i. + Number of submitted presentations (for each, provide a complete citation): 14

j. + Honors/Awards/Prizes for contract/grant employees (list attached)
(This might include Scientific Society Awards/Offices, Selection as Editors, Promotions, Faculty Awards/Offices, etc.)

k. Total number of Full-time equivalent Graduate Students and Post-Doctoral associates supported during this period, under this R&T project number: 0
Graduate Students: 0
Post-Doctoral Associates: 0
Note: The salaries for the graduate students and postdocs involved in the current experiments are paid from AASERT awards, the Packard fellowship and the NSF grant (this is cost-effective due to different overhead charges).

l. + Other funding (list agency, grant title, amount received this year, total amount, period of performance and a brief statement regarding the relationship of that research to your ONR grant)

+ Use the letter and an appropriate title as a heading for your list, e.g.: b. Published Papers in Refereed Journals, or, d. Books and Chapters published.

* Minorities include Blacks, Aleuts, AmIndians, Hispanics, etc. NB: Asians are not considered an under-represented or minority group in science and engineering.

a. Papers submitted to refereed journals, but not published:

J. Stenger, S. Inouye, D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, and W. Ketterle:
Spin domains in ground state spinor Bose-Einstein condensates.
Nature (1998), submitted.

D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle:
Reversible Formation of a Bose-Einstein Condensate.
Phys. Rev. Lett. (1998), submitted.

M. Naraschewski and D.M. Stamper-Kurn
Analytical description of a trapped semi-ideal Bose gas at finite temperature.
Physical Review A, in press.

H.-J. Miesner and W. Ketterle:
Bose-Einstein condensation in dilute atomic gases.
Proceedings of the Symposium on "The Advancing Frontiers of Condensed Matter Science", Philadelphia, Oct. 13-14, 1997.
Solid State Comm., in press.

D. Stamper-Kurn, H.-J. Miesner, S. Inouye, M.R. Andrews, and W. Ketterle:
Collisionless and Hydrodynamic Excitations of a Bose-Einstein Condensate.
Phys. Rev. Lett., in press.

b. Papers published in refereed journals

S. Inouye, M.R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle:
Observation of Feshbach Resonances in a Bose-Einstein Condensate.
Nature **392**, 151-154 (1998).

H.-J. Miesner, D.M. Stamper-Kurn, M.R. Andrews, D.S. Durfee, S. Inouye, and W. Ketterle:
Bosonic Stimulation in the Formation of a Bose-Einstein Condensate.
Science **279**, 1005-1007 (1998).

D.M. Stamper-Kurn, M.R. Andrews, A. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle:
Optical Confinement of a Bose-Einstein Condensate.
Phys. Rev. Lett. **80**, 2072-2075 (1998).

D.S. Durfee and W. Ketterle:
Experimental Studies of Bose-Einstein Condensation.
Optics Express **2**, 299-313 (1998).

M.R. Andrews, D.S. Durfee, S. Inouye, D.M. Kurn, H.-J. Miesner, and W. Ketterle:
Studies of Bose-Einstein Condensates.
Proceedings of the Symposium on "Quantum Fluids and Solids" (QFS 97), Paris, July 20-26, 1997.
J. Low Temp. Phys. **110**, 153-166 (1998).

W. Ketterle and H.-J. Miesner:
Coherence properties of Bose-Einstein condensates and atom lasers.
Phys. Rev. A **56**, 3291-3293 (1997).

M.R. Andrews, D.M. Kurn, H.-J. Miesner, D.S. Durfee, C.G. Townsend, S. Inouye, and W. Ketterle:
Propagation of sound in a Bose-Einstein condensate.
Phys. Rev. Lett. **79**, 549-552 (1997); Erratum: Phys. Rev. Lett. **80**, 2967 (1998).

N.J. van Druten and W. Ketterle:
Two-Step Condensation of the Ideal Bose Gas in Highly Anisotropic Traps.
Phys. Rev. Lett. **79**, 553-556 (1997).

c. Books or chapters submitted, but not yet published

W. Ketterle:
Atom Laser.
McGraw-Hill 1999 Yearbook of Science & Technology,
companion volume to Encyclopedia of Science & Technology, in press.

e. Technical reports/non-refereed papers

H.-J. Miesner and W. Ketterle:
Bose-Einstein condensation in dilute atomic gases and realization of an atom laser.
(Article is a shortened version of the Solid State Comm. paper).
SPIE conference Photonics West, San Jose, California, Jan. 24-30, 1998, in press.

M.R. Andrews, D.S. Durfee, S. Inouye, D.M. Kurn, H.-J. Miesner, and W. Ketterle:
Studies of Bose-Einstein Condensates.
(Article identical to the J. Low. Temp. Phys. paper).
Proceedings of the International Conference on Macroscopic Quantum Coherence, Boston, July 11-13, 1997, in press.

W. Ketterle:
Bose-Einstein-Kondensate - eine neue Form von Quantenmaterie.
Phys. Bl. **53**, 677-680 (1997).

h. Invited presentations at conferences

Bose-Einstein condensation in dilute atomic gases and realization of an atom laser
SPIE conference Photonics West, San Jose, California, Jan. 24-30
(Talk by H.-J. Miesner)

Dynamic Properties of Bose-Einstein Condensates: Formation and Sound at Non-zero Temperatures
ITP Conference on Bose-Einstein Condensation, Institute for Theoretical Physics, Santa Barbara, March 30 - April 4.

Optical Confinement of Bose-Einstein Condensates and the Observation of Feshbach Resonances
ITP Conference on Bose-Einstein Condensation, Institute for Theoretical Physics, Santa Barbara, March 30 - April 4 (Talk by J. Stenger).

Studies of magnetically and optically confined Bose-Einstein condensates
International Quantum Electronics Conference IQEC'98, San Francisco, May 5-7 (Talk by S. Inouye).

Recent Results on Bose-Einstein condensation
DAMOP, 1998 Annual Meeting of the Division of Atomic, Molecular and Optical Physics, Santa Fe, May 27-30 (Talk by H.-J. Miesner).

Single-Mode Atoms: Bose-Einstein Condensation and the Atom Laser.
Gordon Conference on Atomic Physics, New England College, June 30, 1997.

Experimental Studies of a New Quantum Fluid: Bose-Einstein Condensation of Sodium Atoms
European Research Conference on Bose-Einstein Condensation, Il Ciocco, Italy, July 12-17, 1997.

Recent experimental results with Bose condensed atoms
Symposium on Quantum Fluids and Solids (QFS 97), Paris, July 20-26, 1997.

Macroscopic Matter Waves: Bose-Einstein Condensate and Atom Laser
Gordon Research Conference on Nonlinear Optics and Lasers, New London, New Hamshire, July 27-31 (Talk by H.-J. Miesner).

Matter made of matter waves: Bose-Einstein condensation and the atom laser
Symposium on "The Advancing Frontiers of Condensed Matter Science", Philadelphia, October 13-14, 1997.

When atoms behave as waves: Bose-Einstein condensation and the atom laser.
1997 OSA Annual Meeting, Long Beach, October 12-17, 1997.

When atoms behave as waves: Bose-Einstein condensation and the atom laser.
Meeting of the American Institute of Physics Corporate Associates, Dallas, October 27-28, 1997.

i. Submitted presentations

H.-J. Miesner:
Recent Results on Bose-Einstein Condensation.
Bull. Am. Phys. Soc. **43**, 1253 (1998).

W. Ketterle:
Recent Advances in Bose-Einstein condensation.
CLEO/Europe-EQEC'98, Glasgow, Scotland, Advance Program, p. 30.

S. Inouye, M.R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle:
Studies of Bose-Einstein Condensation in Various Hyperfine States.
Bull. Am. Phys. Soc. **43**, 1251 (1998).

D.M. Stamper-Kurn, M.R. Andrews, A.P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle:
Studies of Optically Confined Bose-Einstein Condensates.
Bull. Am. Phys. Soc. **43**, 1251 (1998).

D.S. Durfee, C. Kuklewicz, R. Onofrio, C. Raman, J.M. Vogels, and W. Ketterle:
Experimental Study of Large Bose Condensates.
Bull. Am. Phys. Soc. **43**, 1341 (1998).

D.M. Stamper-Kurn, M.R. Andrews, A.P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle:
Studies of magnetically and optically confined Bose-Einstein condensates
International Quantum Electronics Conference IQEC'98, San Francisco, Advance Program, p. 82.

W. Ketterle:
The new physics of optically trapped Bose-Einstein condensates.
Symposium on Quantum Fluids and Solids (QFS 98), Amherst, Massachusetts, June 9-14, 1997, Book of Abstracts, Paper 9-S2..

H.-J. Miesner, D.M. Stamper-Kurn, M.R. Andrews, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle:
Optische Falle für Bose-Einstein-Kondensate.
Spring meeting of the German Physical Society, Book of Abstracts, SYA2.1.

H.-J. Miesner, S. Inouye, M.R. Andrews, J. Stenger, D.M. Stamper-Kurn, and W. Ketterle:
Beobachtung von Feshbach-Resonanzen in einem Bose-Einstein-Kondensat.
Spring meeting of the German Physical Society, Book of Abstracts, Q51.6.

W. Ketterle:
When atoms behave as waves: Bose-Einstein condensation and the atom laser.
1997 OSA Annual Meeting, Book of Abstreacts, WY1.

D.M. Kurn, M.R. Andrews, H.-J. Miesner, D.S. Durfee, C.G. Townsend, S. Inouye, and W. Ketterle:
Studies of coherence of Bose-Einstein condensates.
1997 OSA Annual Meeting, Book of Abstreacts, WFF16.

D.M. Kurn, H.-J. Miesner, M.R. Andrews, D.S. Durfee, C.G. Townsend, S. Inouye, C. Kuklewicz, and W. Ketterle:
Collective excitations and the nature of sound in a Bose condensed gas.
1997 OSA Annual Meeting, Book of Abstreacts, WNN3.

W. Ketterle
Recent experimental results with Bose condensed atoms.
Symposium on Quantum Fluids and Solids (QFS 97), Paris, July 20-26, 1997, Book of Abstracts, D-I1..

M.-O. Mewes, M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle:
Bose-Einstein-Kondensate - eine neue Form der Quantenmaterie
Verhandl. DPG (VI) **32**, 348 (1997).

j. Honors/Awards/Prizes for contract/grant employees

1997	JSEP fellowhsip for Dan Stamper-Kurn
1997	Humbodt fellowship for Dr. Jörn Stenger
7/1997	Promotion to Chair: John D. MacArthur Professor of Physics (W.K.)
1997	Fellow of the American Physical Society (W.K.)
1998 - 99	Distinguished Traveling Lecturer of the Division of Laser Science of the American Physical Society (W.K.)
1998	Discover Magazine Award for Technological Innovation (W.K.)

l. Other funding

CURRENT SUPPORT

- ONR Augmentation Award for Science and Engineering Research Training (AASERT), "A Quantum Gas of Cold Li Atoms", $ 171,000 for the period 7/1/94 through 6/30/97
- ONR Augmentation Award for Science and Engineering Research Training (AASERT), "Nanokelvin Sodium Atoms", $ 148,000 for the period 6/1/95 through 5/31/98
- Office of Naval Research, Augmentation Award for Science and Engineering Research Training (AASERT), "Study of Bose-Einstein Condensates", $ 148,806 for the period 4/1/98 through 3/31/01

Those AASERT grants are connected to the ONR grant for which this report is provided.

- NSF Career Program, "Atomic Quantum Gases", $ 300,000 for the period 5/1/98 through 4/30/00
- Army Research Office, "Basic Research in Electronics", $ 97,050 for the period 1/98 - 1/01
- David and Lucile Packard Foundation, "Packard Fellow in Science and Engineering", $ 500,000 for the period 9/24/1996 through 9/23/2001
- NASA, "Towards Precision Experiments with Bose-Einstein Condensates", $ 310,000 for the period 2/1/98 - 1/31/03

The major support of our current experiments on Bose-Einstein condensation is provided by ONR and NSF. Both grants are necessary to fund the complex experiment. ARO, NASA and the Packard foundation fund additional projects and people.

PART II

a. Principal Investigator: Wolfgang Ketterle

b. Current telephone number: (617) 253-6815

c. Cognizant ONR Program Officer: Peter Reynolds

d. Program objective:
To develop an intense source of Bose condensed sodium atoms and to study the properties of Bose-Einstein condensates

e. Significant results during last year (100-200 words) - be specific and comment on impact

We had several significant results in the reporting period (6/97 - 5/98):

- Formation of a Bose-Einstein condensate: The phase transition from a thermal cloud into a Bose-Einstein condensate was studied with high time resolution. The condensate formation showed evidence for bosonic stimulation, or matter wave amplification, which is crucial to the concept of the atom laser.
- Study of collective excitations of a Bose gas: Collective excitations of a dilute Bose gas were probed above and below the condensation temperature. Oscillations analogous to Bogoliubov sound, first and second sound were observed.
- Realization of all-optical confinement of a Bose-Einstein condensate: The confinement of Bose-Einstein condensates in an optical dipole trap allows the study of condensates at arbitrary magnetic fields and with arbitrary spin orientation. Of special interest for precision measurements is the zero-magnetic-field case. Furthermore, the optical trap can be used as optical tweezers to move condensates and study them in new situations, e.g. close to surfaces.
- Reversible formation of a Bose-Einstein condensate: Bose-Einstein condensation could be achieved in an reversible way in contrast to the evaporative cooling methods used so far. This was achieved by adiabatically deforming the trapping potential using magnetic and optical forces.
- Observation of Feshbach resonances: The forces between Bose condensed atoms could be altered significantly through so-called Feshbach resonances. Such resonances were observed by varying an external magnetic fields and open new possibilities for the study and manipulation of Bose-Einstein condensates.
- Spinor condensates: We observed the formation of spin domains in Bose-Einstein condensates occupying all three hyperfine spin states of the ground state multiplet. The structure of these domains gave evidence for an anti-ferromagnetic interaction between the atoms. We observed both miscibility and immiscibility of hyperfine components.

BEC is rapidly becoming a new subfield, interdisciplinary between atomic and condensed matter physics with more than fifty active groups. Several techniques which we developed are now used in many other labs. Our quantitative studies of a Bose condensate have been very stimulating for theorists. NASA is taking the first steps towards laser cooling experiments in microgravity. These include atomic clock and BEC experiments.

f. Brief (100-200 words) summary of plans for next year's work

Our recent work on optical trapping of Bose-Einstein condensates demonstrated many new possibilities for future research. We plan to continue the study of spinor condensates, mainly the

dynamics of non-equilibrium mixtures of spin states. Furthermore we plan to develop optical traps with more than one potential well, like in a standing wave. This might allow the observation of the Josephson effect or Bloch oscillations. Bragg scattering might be used to realize a continuous atom laser.

A new source of laser cooled sodium atoms is under construction. It will feature much higher loading rates of the atom trap (at least a factor of ten higher than at present), and improved optical access.

g. List of names of graduate students and post-doctoral(s) currently working on the project:

Graduate students:

Michael R. Andrews (until 4/98)
Dan M. Kurn
Dallin S. Durfee
Shin Inouye
Chris Kuklewicz
Ananth P. Chikkatur

Postdocs:

Hans-Joachim Miesner
Jörn Stenger
Roberto Onofrio
Chandra Raman

PART III

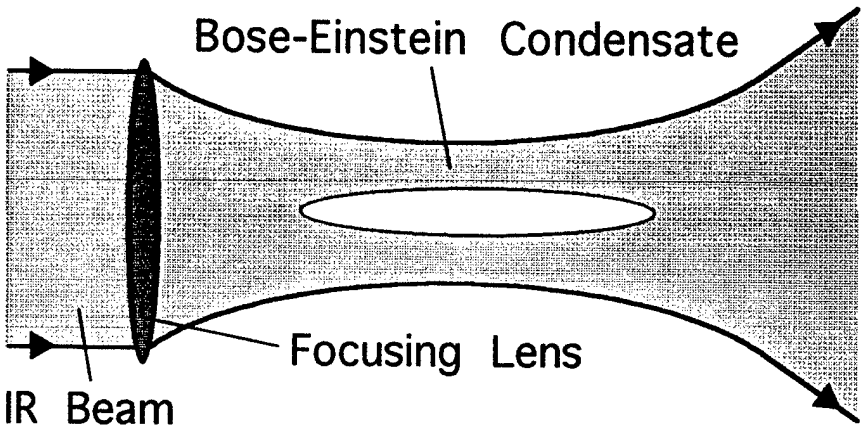
Explanation for the two viewgraphs

1. Our work on the optical trap and Feshbach resonances has provided new ways to manipulate Bose-Einstein condensates. The optical trap provides higher spatial and temporal control than magnetic traps. Furthermore, it allows the free choice of internal spin states or external magnetic bias fields.
The forces between the Bose condensed atoms could be altered by a factor of ten by varying the magnetic bias field around a Feshbach resonance near 900 G. It is now possible to tune the interaction strength between the atoms and maybe to "design" properties of quantum gases.

2. Formation of spin domains in spinor Bose-Einstein condensates. When condensates were prepared in only one (or two) of the hyperfine components of the F=1 ground state, we observed the formation of three distinct spin domains. The equilibrium distribution was independent of the initial distribution and only depended on the total spin angular momentum. The spin domain diagram for spinor condensates is very rich and allows the study of miscible and immiscible superfluids and novel forms of collective excitations.

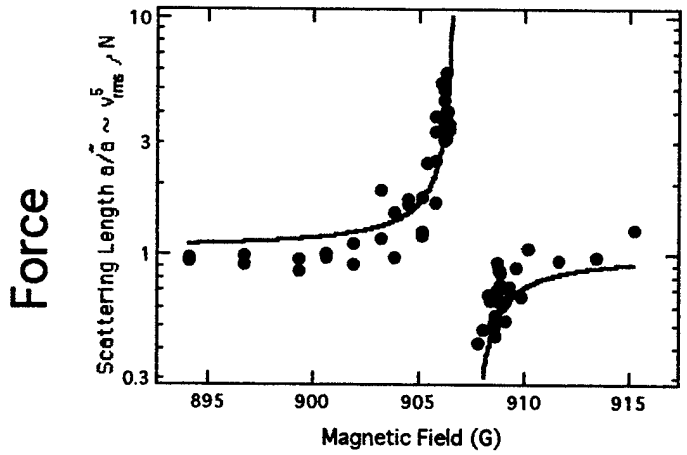
"Ultimate" control over Bose-Einstein condensates

Optical Trap



Optical tweezers for nanokelvin atoms with mW laser power

Feshbach resonances

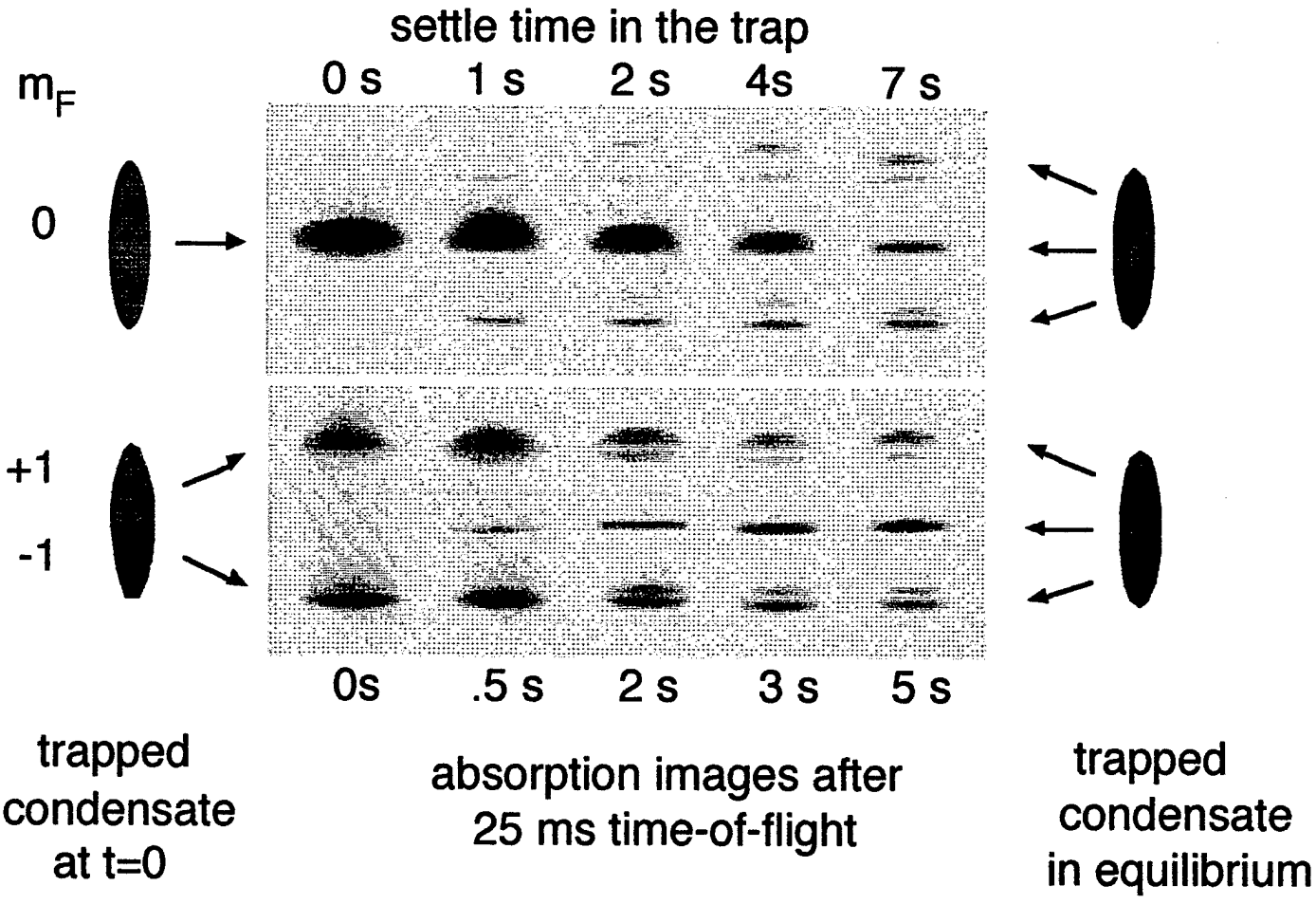


Magnetic Field

"Tuning" the forces between atoms with magnetic fields

Formation of spin domains in single condensates

- multi component condensates
- study of phase diagram
- miscibility and immiscibility in quantum gases



ATTACHMENT NUMBER 1

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(d) Final Patent Report (DD 882)

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